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Geomechanical Simulations Related to UCG Activities

Oleg Y. Vorobiev, Joseph P. Morris, Tarabay H. Antoun and S. Julio Friedmann

Introduction

This paper presents results from a recent investigation into a range of geomechanical processes induced by UCG activities. The mechanical response of the coal and host rock mass plays a role in every stage of UCG operations. For example, cavity collapse during the burn has significant effect upon the rate of the burn itself. In the vicinity of the cavity, collapse and fracturing may result in enhanced hydraulic conductivity of the rock matrix above the burn chamber. Even far from the cavity, stresses due to subsidence may be sufficient to induce new fractures linking previously isolated aquifers. These mechanical processes are very important in understanding the risk of unacceptable subsidence and the potential for groundwater contamination. The mechanical processes are inherently non-linear, involving significant inelastic response, especially in the region closest to the cavity. In addition, the response of the rock mass involves both continuum and discrete mechanical behavior. To better understand these effects, we have applied a suite of highly non-linear computational tools in both two and three dimensions to a series of UCG scenarios. The calculations include combinations of continuum and discrete mechanical responses by employing fully coupled finite element and discrete element capabilities [1, 2].

Calculations of ground subsidence due to pressure drop in a cylindrical cavity

Geertsma [3] derived analytical solution for surface subsidence caused by pressure drop in a disc-shaped reservoir. According to this solution vertical surface displacements caused by the pressure drop ΔP in the cavity are expressed as

$$u_z(r,0) = -2c_m(1-\nu)\Delta PH R \int_0^{\infty} J_1(R\alpha)J_0(r\alpha)e^{-D\alpha} d\alpha \quad (1)$$

The solution is derived based on poroelasticity theory and assumes that all media including the reservoir is characterized by constant elastic properties such as uniaxial compaction coefficient, c_m , and Poisson ratio, ν . Both horizontal and vertical surface displacements are proportional to the thickness of the reservoir, H and its radius, R . The maximum vertical subsidence can be expressed as

$$u_z(r,0) = -2c_m(1-\nu)\Delta PH \left(1 - \frac{\eta}{\sqrt{1+\eta^2}}\right), \eta = D/R, \quad (2)$$

where D is the depth of the reservoir.

For shallow reservoirs, $\eta \leq 1$, the maximum vertical subsidence does not depend on reservoir radius and expressed as $u_z(r,0) \rightarrow -2c_m(1-\nu)\Delta PH$. Uniaxial compaction coefficient, c_m , is defined as the amount of reservoir compaction per unit pressure reduction:

$$c_m = \frac{1}{z} \frac{dz}{dp} \quad (3)$$

Different methods were proposed to evaluate c_m for poroelastic saturated material [3, 4]. In the case of UCG choosing c_m presents a big uncertainty, since it will depend on the details of the cavity collapse and compaction.

To verify that function described above describes surface subsidence due to the cavity collapse, we have performed a 2D calculation of cylindrical cavity collapse under the gravity. Fig.1 shows the mesh used in this calculation. Results of calculated surface subsidence for two cavities of various radii are shown in Fig.2 with points. The solid lines in Fig.2 show calculations using eq. 1, where the compaction coefficient, c_m , was chosen to make a good fit to the analytical solution. For simplicity, the pressure in the cavity was set to zero and the material was assumed to have an elastic response. This resulted in the closure of the cavity. Contact boundaries were set around the cavity to prevent the cavity boundaries from overlapping.

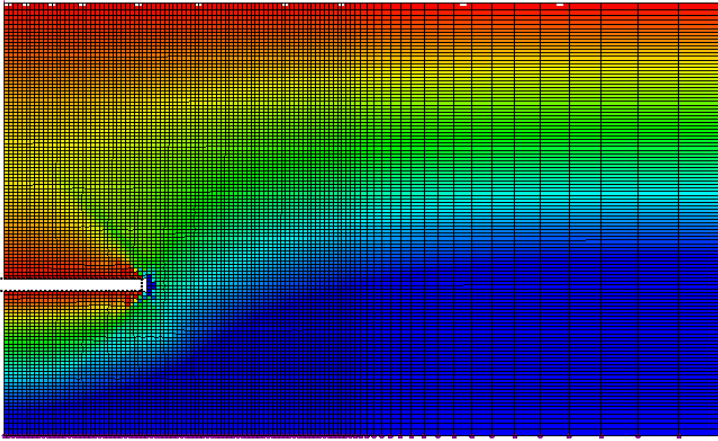


Fig.1 Mesh and vertical stress contours before cavity collapse. Cavity radius, R is 50 m, thickness, H is 5 m and the depth, D is 100 m.

Analytical method developed by Geertsma is based on a number of assumptions, such as constant elastic moduli both for the reservoir and the geologic materials above it, and linear-elastic material response within the frames of continuum mechanics. These assumptions may not be valid closer to the cavity, where the discrete nature of the rock is important. Numerical analysis which does not make these assumptions may be needed to evaluate the surface subsidence due to the cavity collapse and compaction.

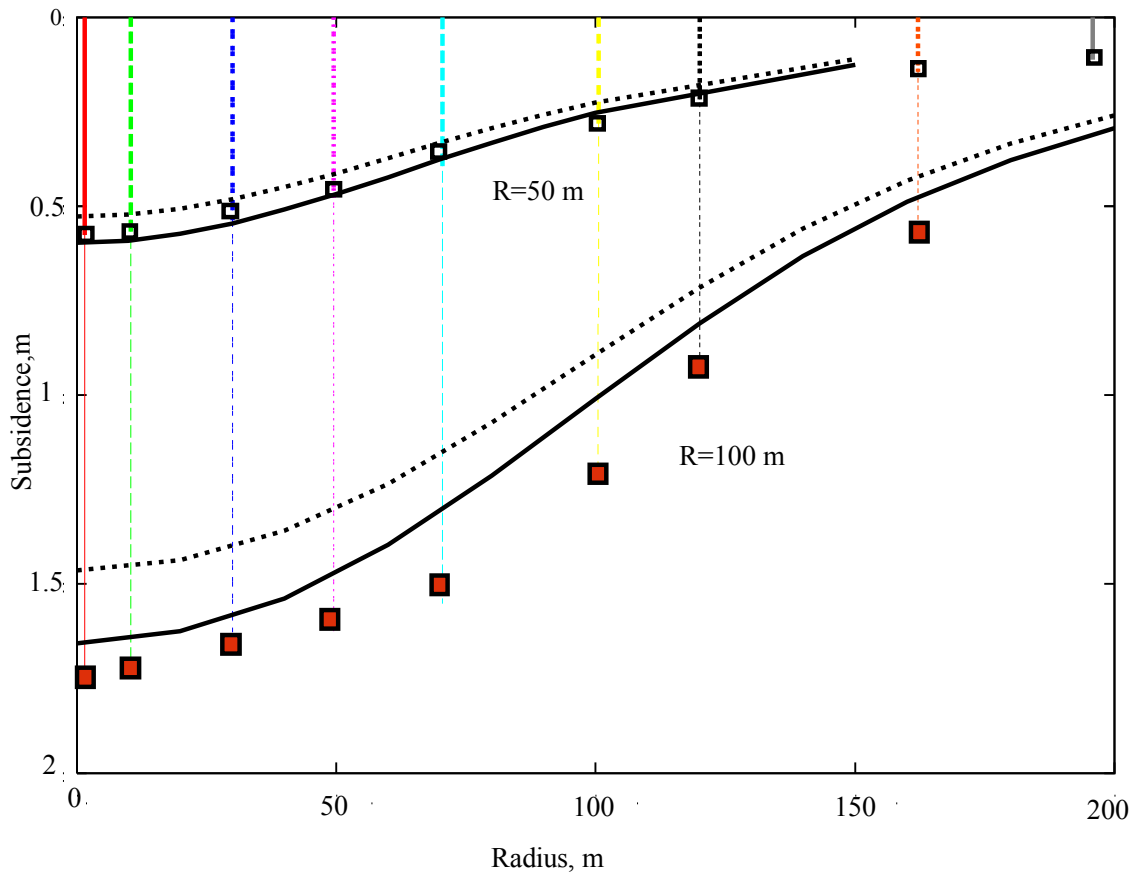


Fig.2 Comparison of the surface subsidence calculations (squares) with the analytical solutions (lines) for two cavities with $R=50$ m and $R=100$ m

Ground subsidence calculations due to UCG activity

The following approach was used to calculate ground subsidence due to UCG activity. The FE mesh was filled with the material pre-stressed in each element to a given lithostatic state. The vertical stress was equal to the weight of the material column above and the two horizontal stresses were initialized to be a fraction of the vertical stress. The mesh was co-oriented with the principal stresses with appropriate pressure boundaries applied at the sides to keep material in equilibrium. Next, elements representing gasified coal were removed and the new equilibrium was found. Removal of the elements caused redistribution of stresses within the system and, as the consequence of that some subsidence of the surface above. Fig.3-4 shows simple 2D examples illustrating this approach. As previous work has shown [2], the discrete nature of the rock around the cavity can control cavity collapse. Fig.3 shows the results obtained with a continuum model, where cavity removal caused elastic response of the rock above. Fig.4 shows that when the joints are introduced into material the cavity may collapse as a result of blocks sliding into the cavity under the stress field induced by the cavity (Fig.5).

Figure 6 shows example of 3D calculation of ground subsidence with the GEODYN-L code [1] for a group of parallel tunnels created by multiple UCG cavities (a

module) in the coal seam after extended UCG operations. For this calculation, the density of the material was 2.51 g/cc, the shear modulus was 12 GPa and the bulk modulus was 20 GPa. A uniform mesh with 120x120x120 elements was used to cover 1 km x 1km x 500 m region. Table 1 shows subsidence at point A above the module for various values of the yield strength for the material used in the calculations. For the yield strength $Y > 0.1$ Gpa material response was purely elastic. For weaker material some plastic deformations are generated around and between the tunnels. The fault shown in fig.6 was modeled using continuum approach.

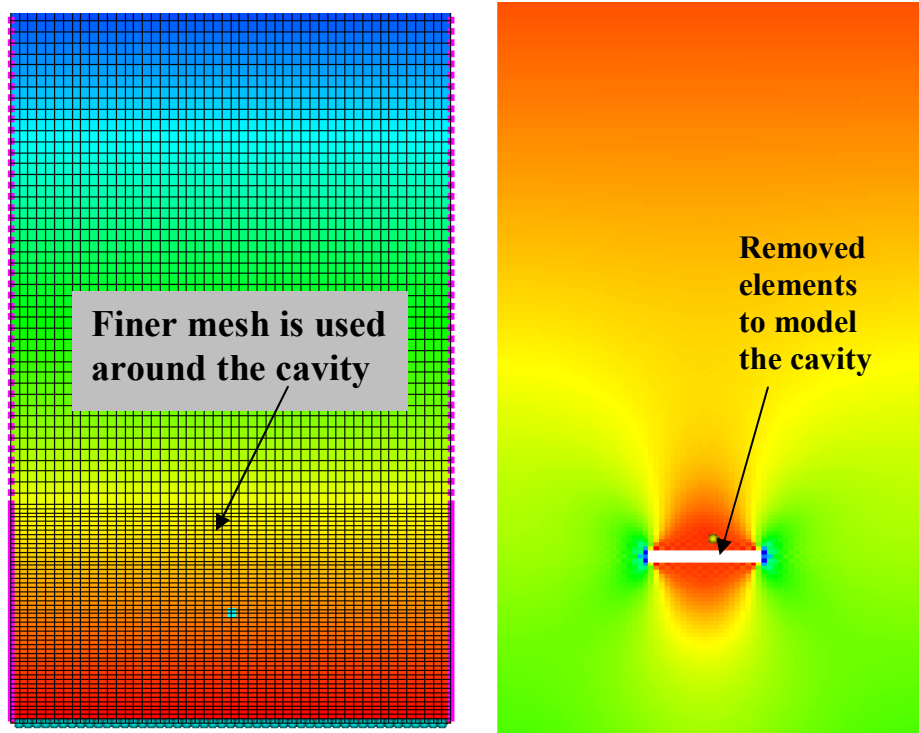


Fig.3 Mesh and vertical stress contours for 2D region and vertical stress distribution after cavity removal.

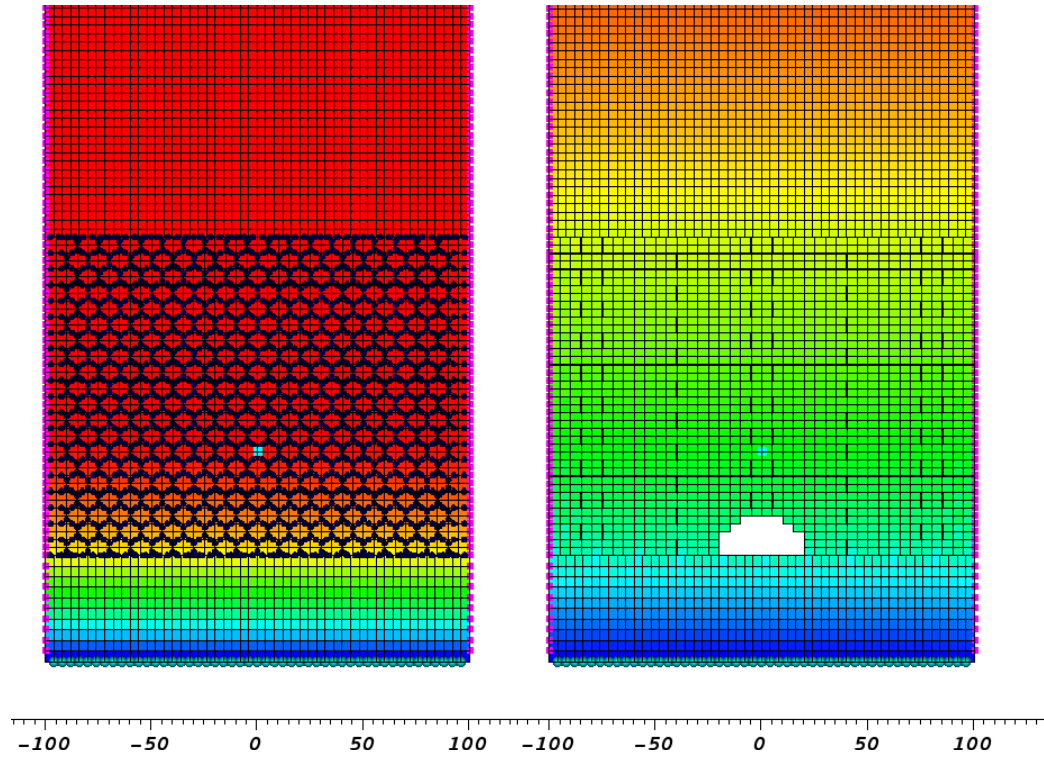


Fig.4 Vertical stress distribution and joints location in coal layer (a), cavity create by element removal (b)

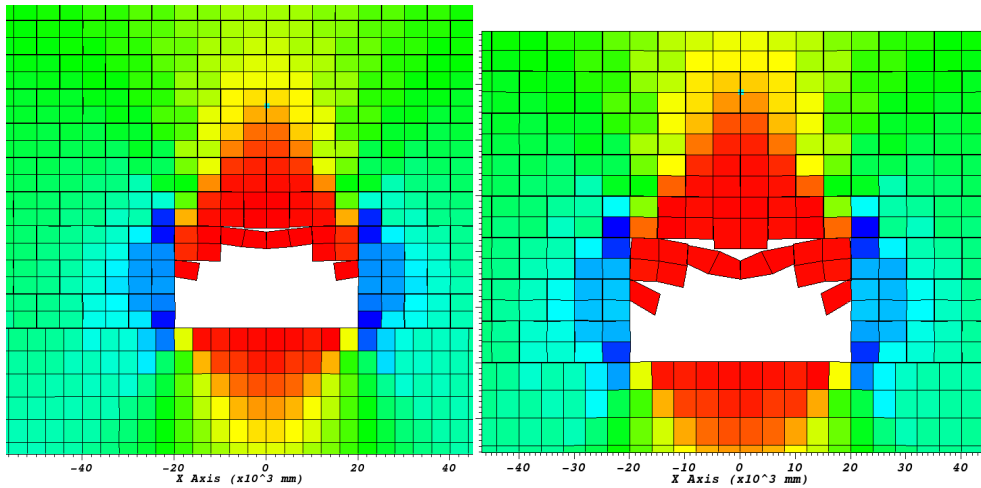


Fig.5 Vertical stress contours for different times during collapse of a cavity in jointed rock.

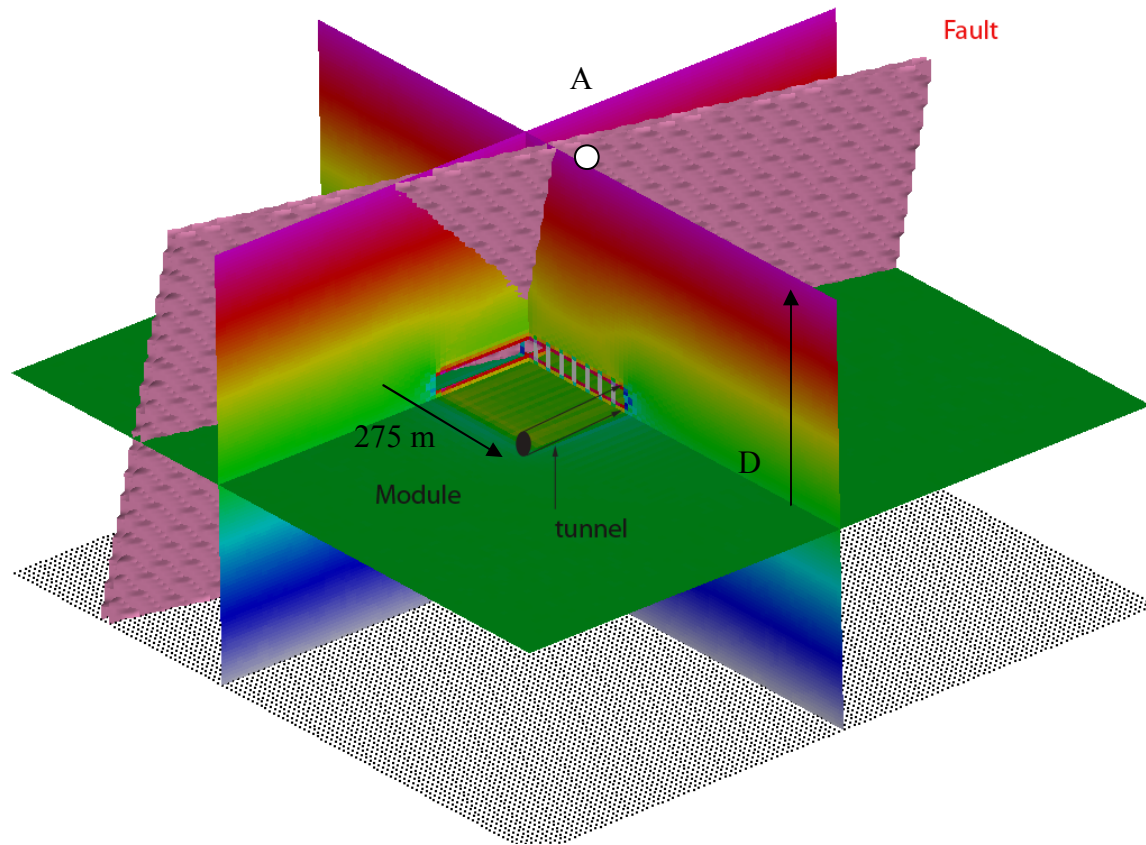


Fig.6 Vertical stress distribution caused by 8 parallel 300 m long tunnels which form a 275 m wide module.

Table 1. Ground subsidence above the module for different strength of the soil (Point A)

Yield strength:	Y=0.1 GPa	Y=0.011 GPa	Y=0.01 GPa
Ground subsidence(mm)	2.5	6	8

Conclusion

Details of the cavity collapse and compaction may be important to evaluate the ground subsidence evaluation due to UCG activity. Discrete methods are needed to capture main features of cavity collapse. A combination of continuum (numerical or analytical) and discrete approaches is probably the best strategy in predicting surface subsidence due to UCG.

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